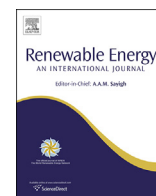


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Tidal energy leasing and tidal phasing

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ABSTRACT

In addition to technical and economic constraints, tidal energy leasing is generally governed by demand for sites which contain the highest tidal streams, and does not take into account the phase relationship (i.e. the time lag) between sites. Here, the outputs of a three-dimensional tidal model are analysed to demonstrate that there is minimal phase diversity among the high tidal stream regions of the NW European shelf seas. It is therefore possible, under the current leasing system, that the electricity produced by the first generation of tidal stream arrays will similarly be in phase. Extending the analysis to lower tidal stream regions, we demonstrate that these lower energy sites offer more potential for phase diversity, with a mean phase difference of 1.25 h, compared to the phase of high energy sites, and hence more scope for supplying firm power to the electricity grid. We therefore suggest that a state-led leasing strategy, favouring the development of sites which are complementary in phase, and not simply sites which experience the highest current speeds, would encourage a sustainable tidal energy industry.

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1. Introduction

Making use of the tides to perform work is not a novel concept – for example around 750 tide mills are known to have been in operation at one time or another along the shores of the Atlantic [1]. However, a relatively new concept is making use of the tides, particularly the kinetic energy of tidal streams, to contribute to significant electricity generation [2]. Concerns about energy security and global warming has fuelled an interest in marine renewables, particularly in nations like the UK which are equipped with an energetic tidal resource [3]. Although tides and tidal currents are predictable, this form of electricity generation, in common with other forms of renewable energy like wind, wave, and solar, is intermittent [4], from the semi-diurnal (twice daily) flood and ebb of the tides, through to spring–neap (fortnightly) variability. However, the timing of high and low water, and flooding and ebbing tidal currents, varies considerably along our coastlines – for example, high tide in Dover (English Channel) occurs around 8 h later than high tide in Leith (Edinburgh) (locations shown on Fig. 1). Therefore, there is scope for exploiting our knowledge of the phase relationship between tidal energy sites by aggregating the electricity generated by a number of geographically distributed sites, leading to firm power supply to the electricity grid [5].

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Consideration of the phase relationship between sites is not reflected in the current leasing process for tidal energy schemes. For example, in the UK, The Crown Estate (as manager of the UK seabed) grants rights for tidal energy developers to operate on the seabed. Although technical and economic factors are important, at present, with the exception of Holyhead Deep (Minesto UK Ltd), developers are exclusively interested in high tidal energy sites (e.g. peak spring tidal currents ≥ 2.5 m/s [6]), as evidenced by the 31 tidal stream sites that are currently leased from The Crown Estate (Table 1). However, it has been suggested that there is minimal phase diversity among these high tidal energy sites [7], and if all such sites were to be developed in parallel, the aggregated electricity supplied to the grid would be characterised by strong semi-diurnal intermittency [3]. The time lag between occurrence of peak flood current at Dover and peak flood current at each of the Crown Estate leased sites is also included on Table 1. This time lag relates to currents, and if we assume that a tidal energy device will generate electricity equally during the flood and ebb phases of the tidal cycle, then an optimal complementary time lag between two sites would be 3.1 h, i.e. a quarter of a tidal cycle. On examination of the timing of peak flood (or ebb) currents, there seems to be more scope for phase diversity among these leased sites than has been suggested by previous studies [3,7]. However, the current study is not constrained by an examination of only the presently leased sites, nor UK waters, and extends such analysis to the wider context of the NW European shelf seas in providing firm power to the electricity

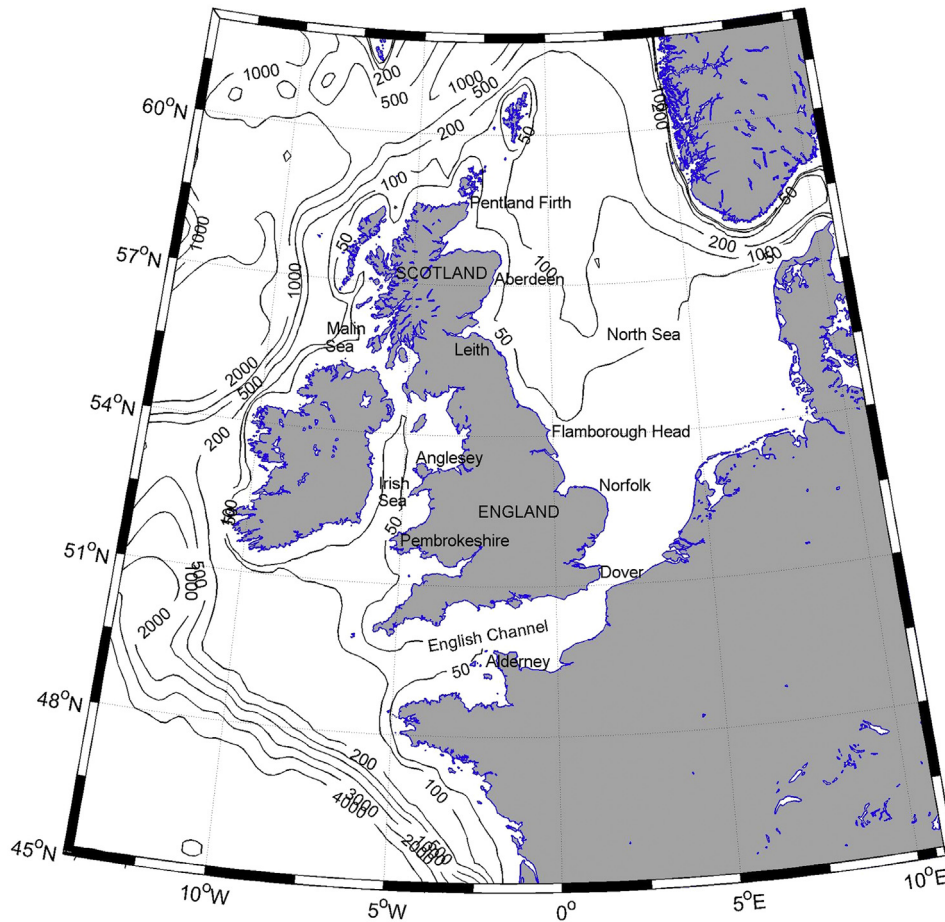


Fig. 1. The northwest European shelf seas. Contours are water depths in metres.

grid in the future, by aggregating sites that exhibit a variety of characteristics, including a range of tidal current amplitudes and phases, and a range of water depths.

Here, we discuss the implications of a leasing strategy that is governed by demand for exclusively high tidal stream regions, and suggest ways in which phase diversity could be increased, such as developing lower tidal stream sites (e.g. peak spring tidal currents ≥ 1.5 m/s [6]) in parallel with high tidal stream development. We also discuss how a state-controlled leasing system, working in conjunction with privatised or centralised electricity networks, could lead to increased phase diversity, and hence the ultimate success of a sustainable tidal energy industry.

We first introduce the study region (the NW European shelf seas; Section 2), then provide an overview of generating electricity from tidal streams (Section 3), discussing tide generating forces, tidal currents, tidal power, and the concept of tidal phasing. We next present the results from a three-dimensional (3D) tidal model of the NW European shelf seas (Section 4), demonstrating the phase diversity that would result from aggregating the electricity generated across a range of tidal current amplitudes. Finally, we consider the characteristics of lower tidal stream sites, and discuss the implications of tidal phasing on leasing strategies, and other considerations such as energy storage, supergrids, and practical and economic constraints on tidal energy extraction (Section 5).

2. The northwest European shelf seas

The NW European shelf seas provide Europe with a world

leading resource for the development of a marine renewable energy industry, and are therefore host to a large number of commercial projects and test centres, such as the EMEC wave and tidal test centre in Orkney, and the MeyGen project in the Pentland Firth (Table 1). Although the wave resource is substantial (e.g. Ref. [8]), and there is scope for exploiting the potential energy contained in the vertical tide (e.g. Ref. [9]), the focus of the present work is on the horizontal tide, i.e. tidal streams.

The NW European shelf seas, located on the northeastern margin of the North Atlantic, are generally shallower than 200 m (Fig. 1). The Celtic Sea, Malin Sea and northern North Sea are exposed to Atlantic waters, with water depths in the range 100–200 m, with the exception of the deeper (600 m) Norwegian Trench in the northeastern North Sea. The Celtic Sea borders the Irish Sea to the north, a semi-enclosed water body containing a north–south orientated channel of depth 250 m. To the east of the Celtic Sea, the English Channel connects to the southern North Sea.

There are regions of the NW European shelf seas which contain some of the largest tidal ranges in the world, e.g. the Bristol Channel and the Gulf of St. Malo. There are three M2 (principal lunar semi-diurnal constituent) amphidromic points of near-zero tidal range in the North Sea, a further one in the North Channel of the Irish Sea, and two degenerate amphidromic points: one in the English Channel, and the other in St. George's Channel [10]. Tidal currents are generally high in the Irish Sea and English Channel, and moderately high in the Celtic Sea and in the southern and western North Sea [11,12]. Since friction gradually removes energy from the tides at the bottom of the water column, the total attenuation in

Table 1

Tidal stream sites currently leased from The Crown Estate (data from www.thecrownestate.co.uk). Time lag indicates time of peak flood currents relative to the timing of peak flood current at Dover. No data (–) indicates that the location could not be adequately resolved due to model resolution. Sources of data were the model of the NW European shelf seas presented in this work, a high-resolution model of the Pentland Firth and Orkney region [20], and a high-resolution model of the Irish Sea, extending into the eastern Malin Sea [6].

Property name	Tenant name	Project status	Time lag (h)
Ness of Duncansby	ScottishPower Renewables UK Limited	In development	–1.5
Westray South	Westray South Tidal Development Limited	In development	+1.3
Brough Ness	Sea Generation (Brough Ness) Limited	In development	3.4
SeaGen, Strangford Lough	SeaGeneration Limited	Operational	–
EMEC Fall of Warress	EMEC Limited	Operational	+1.1
Kyle Rhea	SeaGeneration (Kyle Rhea) Limited	In planning	–
Sound of Islay	ScottishPower Renewables UK Limited	Pre-construction	–
Inner Sound	MeyGen Limited	In planning	+0.6
Ness of Cullivoe, Shetland (Yell Sound)	Nova Innovation Limited	In construction	–
Isle of Islay (West Islay)	DP Marine Energy Limited	In development	+0.2
Skerries	Sea Generation (Wales) Limited	Pre-construction	+5.6
Bluemull Sound	Nova Innovations Limited	In planning	–
EMEC Shapinsay Sound	EMEC Limited	Operational	+0.8
St Davids Head (Pembrokeshire)	Tidal Energy Developments South Wales Limited	In development	–2.4
Fair Head	DP Marine Energy Limited & DEMA Blue Energy NV	In development	–1.7
Torr Head	Tidal Ventures Limited	In development	–0.6
Strangford Lough	Minesto UK Limited	Pre-construction	–
Lashy Sound	Scotrenewables Tidal Power Limited	In development	+0.9
Perpetuus Tidal Energy Centre (PTEC)	Isle of Wight Council	In construction	–0.1
Sanda Sound	Oceanflow Development Limited	In construction	–
Mull of Kintyre (Argyll)	Argyll Tidal Limited	In development	–0.5
Brims Tidal Array	Brims Tidal Array Development Limited	In development	+1.4
Ramsey Sound	Tidal Energy Limited	Pre-construction	–2.7
Portland Bill	Marine Current Turbines Limited	In planning	+0.3
North Devon Demonstration Zone	Wave Hub Ltd	In planning	+1.6
Holyhead Deep	Minesto UK Ltd	In planning	+3.4
West Anglesey Demonstration Zone	Mentor Mon Cyf	In planning	+3.6
Stronsay Firth	EMEC Limited	In planning	+1.7
Islay Demonstration Zone	EMEC Limited	In planning	–0.3
Mull of Galloway	Marine Current Turbines Limited	In planning	+3.5
Strangford Lough	Marine Current Turbines Limited	In planning	–

large seas, e.g. the North Sea, is pronounced [13,14]. In the North Sea, the propagation of the tidal wave is cyclonic. The tidal wave enters the North Sea by travelling southward along the east coast of Scotland, where the tidal currents and elevations are much greater than near Denmark and Norway, at the end of the tide's transit.

Regions of high tidal currents throughout the NW European shelf seas are concentrated in areas where there is a bathymetric enhancement or topographic restriction, e.g. through straits such as the Pentland Firth [15] and the Alderney Race [16], or past headlands such as Portland Bill in the English Channel [17] and the Skerries to the northwest of Anglesey [18]. However, the sea space at such highly competitive high energy sites is limited, and it is likely that concentrated exploitation of such sites could lead to significant feedbacks between energy extraction and the resource [16].

3. The physics of tidal energy

Tide generation forces lead to the propagation of tidal waves, which can generate strong tidal currents in shelf sea regions. Such regions of strong tidal flow are suitable for electricity generation when intercepted by arrays of tidal energy convertors, but the phase of such electricity generation can vary considerably between shelf sea regions.

3.1. Tide generation forces

The tide generating force is produced by the gravitational attraction between Earth and the moon and sun, in combination with the rotation of the Earth-moon and Earth-sun systems. The tide generation due to the moon arises from an imbalance between

the forces acting on a particle due to the gravitational attraction of the moon, and the centrifugal force due to the Earth's rotation about the centre of gravity of the Earth-moon system [19]. The balance between these forces is exact only at the centre of the Earth; at all other points on the Earth's surface, the small imbalance in these forces results in a tide generating force. The sun exerts a similar force, with a magnitude of approximately 50% of the moon's force, and together these forces act on the waters of the ocean to drive the tides. Since a lunar cycle is 29.5 days, and the Earth rotates on its axis every 24 h, the principal lunar semi-diurnal constituent, M2, has a period of about 12 h and 25.2 min. As time on Earth is measured relative to the rotation of the Earth, the principal solar semi-diurnal constituent, S2, has a period of exactly 12 h. Although the tidal signal is considerably distorted as it interacts with continents, together the M2 and S2 constituents dominate the tidal signal over the NW European shelf seas, and their superposition explains the semi-diurnal (twice daily) and spring–neap (fortnightly) modulation of the tides.

3.2. Tidal currents

As the tidal wave generated in the deep ocean propagates onto the shelf seas (water depths <200 m), it interacts with bathymetric and topographic features. Combined with the effects of Coriolis, this results in the complex tidal signal observed over the shelf seas. The pressure gradient due to phase differences within the vertical tide can lead to very strong tidal currents in many regions, such as the Pentland Firth [20]. The distribution of M2 current speeds over the NW European shelf seas is shown as blue circles in Fig. 2, using output from a 3D ROMS (Regional Ocean Modelling System [21]) model of the region which has a horizontal curvilinear grid, with a

longitudinal resolution of $1/24^\circ$ and variable latitudinal mesh size ($1/32^\circ \sim 1/51^\circ$) [22]. Such a model resolution, although considered relatively high resolution (around 2.8 km) for a shelf-scale study, will clearly not resolve many of the leased sites that reside in narrow channels (e.g. Ramsey Sound and Strangford Lough). However, such a model resolution applied at shelf-scale does allow us to resolve most of the sites around the NW European shelf which contain considerable sea-space, and are therefore essential in the development of a sustainable tidal energy industry. If we restrict our analysis to water depths in the range 25–50 m, i.e. a suitable depth range for first generation tidal energy devices [e.g. 7], the distribution follows the red crosses in Fig. 2. It is clear that the majority of the shelf seas, and so the theoretical tidal energy resource, based on the M2 constituent alone, resides in currents which are <1 m/s, with a significant shift in emphasis to higher tidal current speeds (>1 m/s) when this is constrained by water depths in the range $25 < h < 50$ m. Therefore, sea space at the higher tidal stream sites is limited and, regardless of phase diversity which is the focus of this paper, it will at some stage in the marine renewable energy roadmap become necessary to exploit deeper water/lower tidal stream sites.

3.3. Tidal power generation

Tidal turbines harvest the kinetic energy of tidal flow and, although many competing designs exist, the horizontal axis configuration (similar in appearance to a typical wind turbine) is presently the most favoured design [2]. The instantaneous power density of a tidal flow is

$$\frac{P}{A} = \frac{1}{2} \rho U^3 \quad (1)$$

where A is the cross-sectional area of flow intercepted by the device, ρ is water density, and U is current speed. Since P is a function of U^3 , it is clear why developers seek high tidal stream sites. For example, with a turbine diameter of 20 m, and neglecting device efficiency and feedbacks between energy extraction and the resource, the net power generated over a 24 h period would be 1.7 MWh for a 1 m/s current speed, but this increases by almost a

factor of 30–45.4 MWh for a 3 m/s current speed (Fig. 3). However, as noted in the previous section, and in Fig. 2, such regions of strong tidal flow are severely limited (of order 0.01% of the area) over the NW European shelf seas.

3.4. Phase diversity

Most tidal energy developers, researchers and sailors are familiar with co-tidal charts, which show the amplitude and phase of the vertical component of a particular tidal constituent, for example M2. Further, the amplitude of the tidal currents produces a plot (Fig. 4a) which is familiar from products such as the Atlas of UK Marine Renewable Energy Resources [23], showing the high tidal stream sites throughout the NW European shelf seas; for example the Pentland Firth and NW Anglesey. However, what is not currently considered, and yet which is crucial for the sustainability of a tidal energy industry, is the phase of the tidal currents. Instantaneous velocity u for the M2 tidal constituent is

$$u = H_u \sin(\omega_{M2} t + g_u) \quad (2)$$

where H_u and g_u are the M2 tidal current amplitude and phase, respectively, ω_{M2} is the angular frequency of the M2 tidal constituent, and t is time. Since tidal energy devices will extract energy on both flood and ebb phases of the tidal cycle, we are interested in the absolute value of u , and for $t = 0$

$$|u| = H_u |\sin(g_u)| \quad (3)$$

and so we can characterise the phase relationship between sites using $|\sin(g_u)|$ (Fig. 4b); hence two ideal complimentary sites will have a difference in $|\sin(g_u)|$ of 1 (which represents a time lag of around 3.1 h, i.e. a quarter of a tidal cycle). Examining Fig. 4b in some detail, and in conjunction with the plot of current amplitude (Fig. 4a), it is clear that the electricity generated by many of the high tidal energy sites would be in phase. For example, the Pentland Firth ($H_u > 2.8$ m/s; lag ~ 2.8 h) is close in phase to the high tidal stream sites along the east coast of Scotland (lag ~ 2.4 h north of Aberdeen) and England (lag ~ 3.0 h at Flamborough Head), and these sites are also in phase with key sites in the English Channel, such as the Alderney Race (lag ~ 2.6 h). Further, in the Irish Sea, Pembrokeshire (lag ~ 0.7 h) is approximately in phase with NW

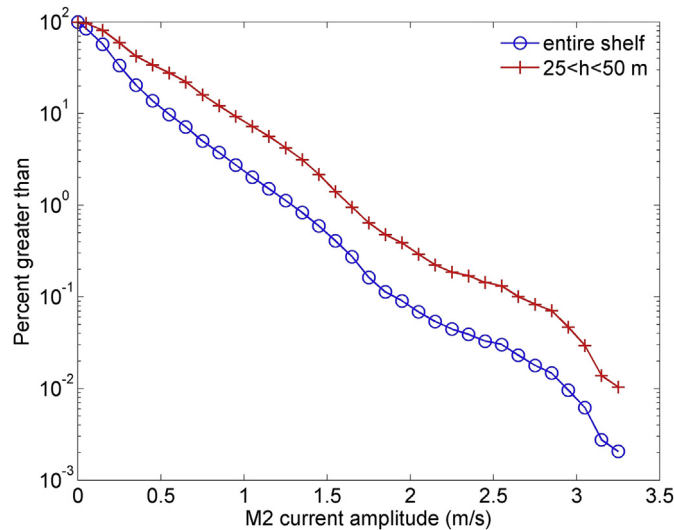


Fig. 2. Cumulative distribution of M2 current speed over the entire NW European shelf seas (blue circles), and only in regions of the shelf with water depths that are in the range $25 < h < 50$ m (red crosses). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

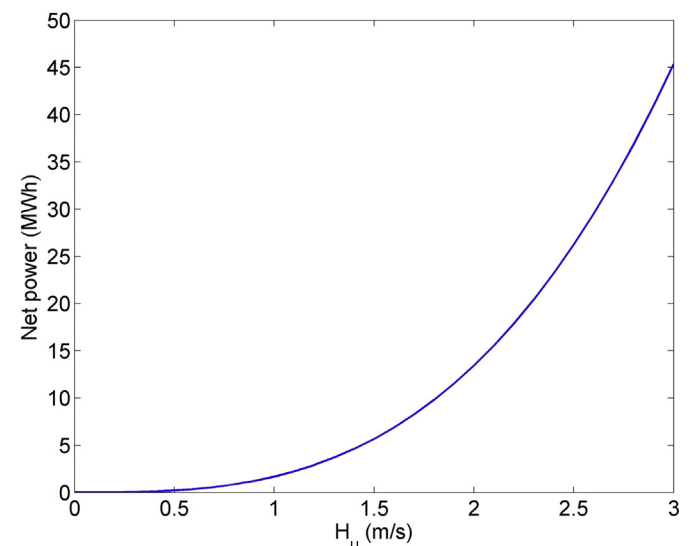


Fig. 3. Net power generated by a 20 m diameter turbine over a 24 h period for a range of M2 tidal current amplitudes, H_u .

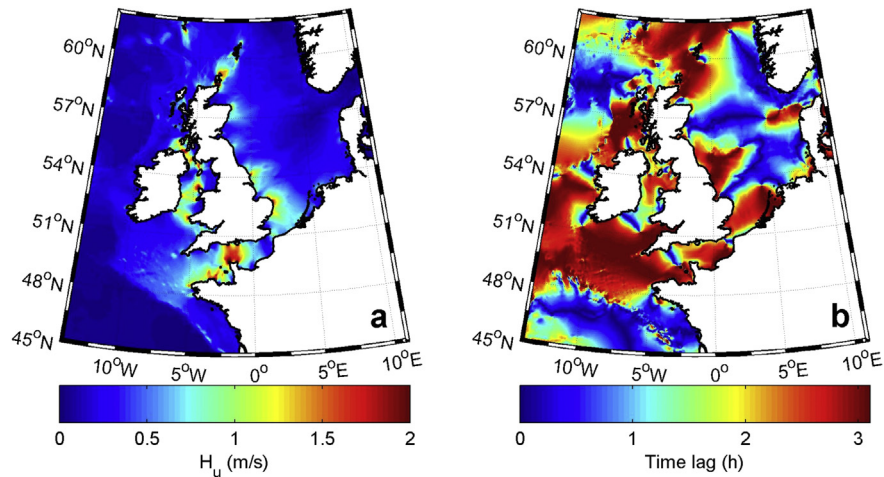


Fig. 4. M2 tidal current (a) amplitude and (b) phase over the NW European shelf seas. (a) is a plot of the semi-major axis of the M2 tidal current ellipse, and (b) is a plot of $T_{M2}[\sin(g_u)]/4$, where T_{M2} is the period of the M2 tidal constituent (approximately 12.42 h), and g_u is tidal current phase.

Anglesey (lag ~0.8 h). It is clear from Fig. 4 that significantly more phase diversity can be introduced into a large-scale tidal energy strategy by considering lower tidal stream sites in addition to developing regions of strong tidal flow. For example, if we consider the lower tidal stream sites ($H_u = 1.5$ m/s) further offshore of Anglesey, in contrast to the higher tidal stream sites ($H_u = 2.5$ m/s) closer to the coast, the phase lag can be increased by around 0.6 h over a relatively short distance.

The significance of phase diversity between different tidal current amplitude sites can be seen clearly if we plot the distribution of phase for a range of M2 tidal current amplitudes throughout the NW European shelf seas (Fig. 5). The higher tidal stream sites ($H_u > 1.5$ m/s) have clearly defined peaks at around 2 h and 8 h (i.e. approximately a quarter-diurnal difference), whereas considerably more phase diversity is introduced as we consider progressively lower tidal stream sites.

4. Aggregated power output

Power density (Eq. (1)) cannot be spatially aggregated to calculate the tidal energy resource over a geographic region [24]. Rather, we assume a single 20 m diameter turbine per model grid cell, to calculate the theoretical (undisturbed) power output

$$P = \frac{1}{2} C_p \rho A u^3 \quad (4)$$

(where $C_p = 0.35$ is assumed device efficiency), which can be aggregated over a geographic region. By way of example, we apply Eq. (4) to selected sites which exhibit a range of phase and amplitude diversities (Fig. 6a), assuming a turbine diameter (or 'equivalent turbine diameter', i.e. representing an equivalent swept area using a number of smaller devices) of 20 m – see Table 2 for further details of site characteristics. Aggregating a number of discrete sites in two scenarios, and scaling the number of devices at each site to the scale of power output in the Pentland Firth, results in time series of power output with considerably different characteristics (Fig. 6b). This figure demonstrates how careful consideration of phase diversity can lead to more continuous power output through minimising periods of low aggregated power production. Using the M2 tidal current amplitude H_u , we applied Eq. (4) to a range of velocity bins (0.5–0.75, 0.75–1.0, 1.0–1.25, 1.25–1.5, 1.5–1.75, and >1.75 m/s) throughout the NW European shelf seas to calculate the aggregated (undisturbed) power generated over an M2 tidal cycle

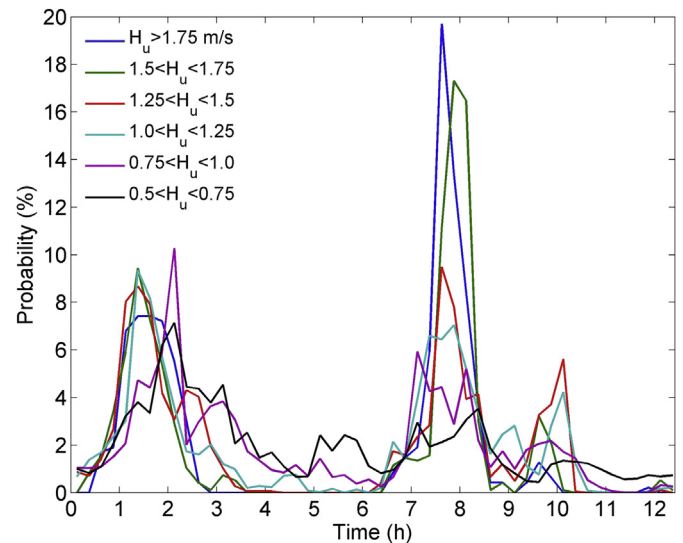


Fig. 5. Distribution of phase (time relative to Greenwich) for a range of M2 tidal current amplitudes (H_u) throughout the NW European shelf seas.

(Fig. 7). These values of aggregated power provide a comparison of how the phase in electricity generation varies between different velocity ranges over the NW European shelf seas. Further characteristics of the aggregated regions are provided in Table 3, including an estimate of how M2 tidal current amplitudes relate to peak spring tidal currents. Examining the high tidal stream sites first ($H_u > 1.75$ m/s), there is very strong semi-diurnal intermittency, with peaks in power of around 270 MW, interspersed with prolonged periods of relatively low (minimum = 6 MW) electricity generation, reflecting the characteristic that there is minimal phase diversity among the high tidal stream sites of the NW European shelf seas (Fig. 4b and Fig. 5). Examining the lower current speeds, there is clearly scope for minimising the time periods of low electricity generation due to increased phase diversity. For example, in the range $0.5 < H_u < 0.75$ m/s, the peak power of 160 MW is accompanied by a minimum power of 70 MW over the tidal cycle. However, it should be noted that an order of magnitude increase in area would be required to sustain electricity generation above such a threshold throughout the tidal cycle (Table 3), and so a blend of lower and higher tidal stream sites would likely offer the optimum

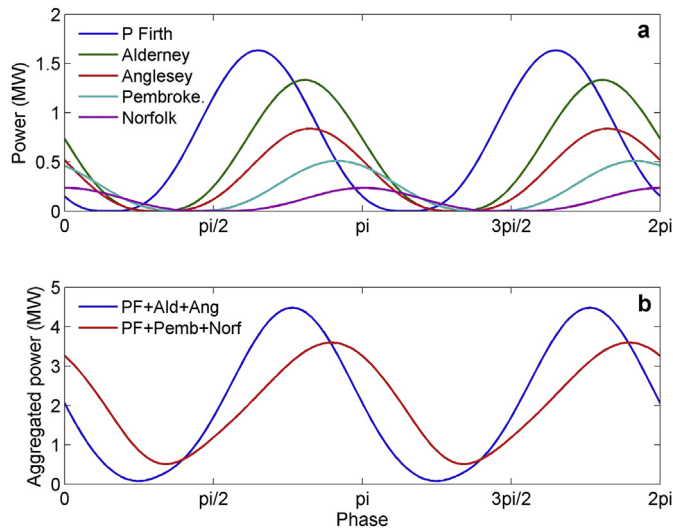


Fig. 6. Power output at a number of discrete tidal energy sites distributed over the NW European shelf seas, based on Eq. (4). (a) is the power generated by a 20 m diameter device (or an 'equivalent turbine diameter') over an M2 tidal cycle, and (b) is the power output for two aggregation scenarios, scaling the number of devices at each location to match peak power output in the Pentland Firth – the most energetic site. In (a) P Firth = Pentland Firth and Pembroke = Pembrokeshire. In (b) PF = Pentland Firth, Ald = Alderney, Ang = Anglesey, Pemb = Pembrokeshire, and Norf = Norfolk. Locations provided on Fig. 1, and characteristics for each site provided in Table 2.

Table 2
Characteristics of locations used in calculations to generate Fig. 6.

Location	M2 current amplitude (m/s)	n turbines ^a
Pentland Firth	3.1	1.00
Alderney	2.9	1.23
Anglesey	2.5	1.95
Pembrokeshire	2.1	3.20
Norfolk	1.6	6.91

^a Equivalent number of turbines required to scale each site to the power output of the Pentland Firth.

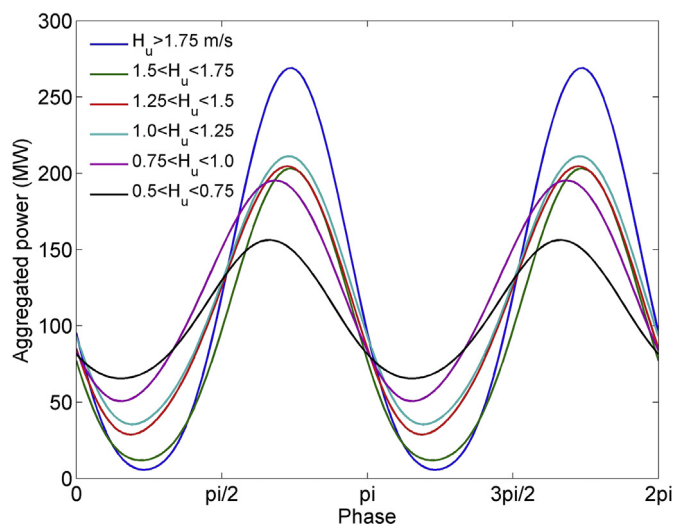


Fig. 7. Aggregated power generated over a tidal cycle for various M2 tidal current amplitude ranges throughout the NW European shelf seas.

sustainable solution to phase diversity.

5. Discussion

Our analysis of tidal current phasing throughout the NW European shelf seas reveals that more phase diversity is offered by lower tidal flow regions (peak spring tidal currents ≥ 1.5 m/s), compared to the phase diversity offered by high tidal flow regions (peak spring tidal currents ≥ 2.5 m/s) (Fig. 7). In particular, and in agreement with previous studies of the region [7,3], the high tidal flow regions of the NW European shelf are generally in phase with one-another (Fig. 4). Therefore, should all these high tidal flow regions be developed, the aggregated electricity generated would be characterised by strong semi-diurnal intermittency. Clearly, development of lower tidal stream sites would diversify this phasing, and generate firmer power with less intermittency (Fig. 7). However, it is important to note that these lower tidal stream sites also experience intermittency over semi-diurnal timescales, and that the peak in aggregated electricity generation would be shifted by at best 1.25 h for lower tidal stream sites, in comparison to high tidal stream sites (Fig. 7). Further, it is important to consider the cost associated with exploiting lower tidal stream regions, since the number of turbines (or equivalent swept area) installed would need to increase by an order of magnitude compared to high tidal energy sites (Fig. 3). Finally, less energetic tidal stream sites are characterised by low eccentricity (i.e. more rotary currents), in contrast to the rectilinear nature of high tidal stream sites [6]. This has implications on the device technology suitable for these low tidal stream regions, with particular emphasis on fixed versus yawing devices [25].

Since leasing for tidal energy schemes is currently driven by demand for high tidal stream sites, this creates a scenario where the majority of tidal electricity generation for a country with an energetic tidal resource like the UK could be in phase. This is in contrast to the wind energy sector because, since the wind resource is governed by large-scale atmospheric circulation, there is no particular pattern to wind phasing throughout a country the scale of the UK. Therefore, leasing for multiple geographically distributed wind energy arrays need not account for phase, and so there would be no appetite for this aspect of the leasing process to be centrally controlled. In contrast, as we have demonstrated here, phase is an important consideration in optimising large-scale tidal energy resource exploitation, and so it could be useful for the sustainability of the tidal energy industry if the leasing strategy accounted for the phase relationship between sites, in addition to the magnitude of the resource.

A timescale issue which tidal stream energy alone cannot address, regardless of the phase relationship between sites, is intermittency over the spring–neap cycle. This longer timescale issue occurs simultaneously throughout the world, since it is governed by the lunar cycle, and so cannot be compensated through optimal site selection. In common with tidal stream energy, the potential energy contained within the vertical tide (tidal range) will also be significantly lower during neaps, in contrast to springs. Therefore, if marine energy is to make a significant contribution to large-scale electricity generation, it will be necessary to supplement it with electricity generated at independent timescales, e.g. via waves and offshore wind. One concept which has been suggested in the past is the development of a multiple-resource supergrid [26], which would facilitate the aggregation of discrete tidal energy sites investigated here, and also allow these locations to be connected to other intermittent renewable energy sources operating on various timescales, such as waves and offshore wind. Although such a concept would be difficult to implement in practice, due to cost and the level of international cooperation that

Table 3

Characteristics of the regions used to calculate the aggregated power plotted in Fig. 7. H_u is the M2 tidal current amplitude. The estimate of the equivalent peak spring tidal current is based on analysis of all shelf sea regions where $H_u > 0.5$ m/s, which yields the result that the M2 tidal current explains 74% of the spring tidal current (with a standard deviation of 0.7%).

H_u range (m/s)	Peak spring tidal current (m/s)	n turbines	\bar{P} (GW)	min(P) (GW)
>1.75	>2.36	474	0.122	0.006
1.5–1.75	2.03–2.36	965	0.097	0.012
1.25–1.5	1.69–2.03	1833	0.112	0.029
1.0–1.25	1.35–1.69	3554	0.118	0.035
0.75–1.0	1.01–1.35	7743	0.121	0.051
0.5–0.75	0.68–1.01	18944	0.108	0.066

would be necessary, it might also be possible to introduce storage into the supergrid, e.g. through pumped hydroelectric schemes [27], hence compensating for intermittency. It should also be noted that much of the high tidal and wave energy resource resides in regions that are remote from major demand [7,26], and hence subject to significant transmission losses [28]. This further encourages the development of lower energy sites which are (a) out-of-phase with high energy sites, and (b) potentially closer to regions of high electricity demand.

This study of phase diversity was exclusively concerned with the theoretical resource, and did not account for practical and economic influences on site selection. For example, many of the high tidal stream sites, although in phase with one-another, are relatively close to the coast, thereby minimising cabling costs, and in relatively shallow (in the range $25 < h < 50$ m) water, thereby minimising installation costs. In contrast, the development of lower tidal stream sites would have additional costs due to likely increased distance to shore, and deeper water installation. Further, the proximity of infrastructure and demand centres are essential factors in site selection, as are site flow characteristics related to tidal constituents in addition to the M2 considered in this analysis, e.g. minimal variance between spring and neap tidal flows described by the S2/M2 tidal current amplitude ratio, and factors related to the selected technology for a site, e.g. capacity factor [29]. Finally, developing devices to operate, and maintaining these devices, in regions of strong tidal flow is a challenging position for the tidal industry to grow from. It could be possible that developing first generation devices to exploit lower tidal streams might be a less challenging position for the industry to progress from, before fully committing to the challenges associated with operating in regions of strong tidal flow. This could be considered analogous to the modest growth of the wind industry from the 1970s to present, and it could be suggested that low tidal stream sites, with the advantage of increased phase diversity, could have an important role in such growth for the tidal stream industry.

6. Conclusions

In this article, we analysed the outputs of a 3D tidal model of the NW European shelf seas to demonstrate that one strategy for encouraging a sustainable tidal energy industry could be to consider the parallel development of both low and high tidal stream sites, due to the phase diversity offered from aggregating electricity generated across a range of tidal current amplitudes. Although technical and economic constraints are important, this suggests that a state-led leasing process should be considered, since the current leasing process is primarily driven by demand for high tidal stream sites.

It would be useful for future studies of phase diversity to consider additional tidal constituents (particularly the principal semi-diurnal solar, S2, constituent), and to also consider marine renewable energy sources acting on other timescales, e.g. waves,

and to apply optimisation algorithms to determine optimum renewable energy roadmap scenarios. Further, such a study would be advised to include feedbacks between energy extraction and the resource, and to examine timescales of relevance to stochastic processes, e.g. seasonal, inter-annual, and inter-decadal.

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